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EVALUATION OF THE TECHNICAL FEASIBILITY AND EFFECTIVE COST OF VARIOUS WAFER THICKNESSES FOR THE MANUFACTURE OF SOLAR CELLS

JPL CONTRACT NO. 955077

SECOND QUARTERLY PROGRESS REPORT

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SOLAREX CORPORATION
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ABSTRACT

Fourteen wafering characterization runs have been completed on the Yasunaga wire saw. Wafer thickness/taper uniformity is excellent. Several alterations and design adjustments have been made, facilitating saw operation. A wafering characterization cycle has been initiated, and is close to completion. A cell characterization cycle has been initiated. Panel design, construction and evaluation will begin during the next quarter.

Introduction

Today, the most expensive part of a silicon solar cell is the high purity silicon from which it is fabricated. In terms of watts delivered per kilogram of silicon used, today's cells are far more expensive than most potential photovoltaic applications can tolerate. The purpose of this program is to evaluate the impact on these costs of thin wafer/low kerf loss wire sawing of silicon using the Yasunaga wafering system. The optimum wafering conditions for best technical and economic results will be determined by evaluating the effect on cell performance of a matrix of wafering parameters. Many of the defined wafer characterization runs have been completed. Cell processing and electrical evaluations have been initiated.

The JPL owned Yasunaga YQ-100 is a continuous-feed multiple-wire free-abrasive saw. It is described in the LSSA Project Task Report, "Multi-Wire Slurry Wafering Demonstrations", No. DOE/JPL-1012-78-7. Saw operation problems and solutions have been addressed this quarter.

Summary of Progress

The Wire Saw

During this quarter, we have begun to solve the many problems associated with the operation of the Yasunaga Wire Saw System. A 3/4 hp constant torque DC electric motor and electronic motor speed controller were adopted to the Yasunaga supplied wire respooler. Although the problem of the lack of direct coupling between the spooling motor and the reciprocating wire guide remains, the renovated system now reliably spools 4, 6 and 8 mil wire.

The wire winder modification has made it possible to actually spool certain wires for the first time. Another concurrent problem with wire has occured with Yasunaga cast aluminum wire spools. Six spools failed. Typical failures are illustrated in Figures 4 and 5 in our last Quarterly Technical Progress report. The lateral stresses which caused the breakage are caused by wire lay (very close and tight) plus, in the case of 8 mil wire, the added tension specified for this high strength wire. Six spools were broken, three on the saw after it was wired-up and running and three during the spooling operation. Many variations in the spooling procedures were tested in an effort to reduce the problem, including:

varying the spooling rates.

guiding the wire lay manually (away from the spool walls without exceeding the angle of repose of the wire building up toward the center of the spool.)

monitoring and adjusting the tensioning drag to avoid any effects of heat build-up.

Using minimum prescribed winding/wafering tension.

Three steel spools, designed and ordered in October, to resist the deformation of tensioned wire, have been received. Test runs during this reporting period indicate that the problem of hub fracture resulting from lateral stress on the spools has been eliminated by use of these spools. Proper spooling according to the above mentioned variations regarding rate, guiding, heat and tension must, however, be maintained since removable steel rim posts utilized from Yasunaga spools can be slightly deformed. This does not break spools but it can hinder proper unwinding of wire and break wires during a wafering run. These spooling variations are important and not mentioned in the Yasunaga spooling instructions.

A problem in the wafering of round ingots, is that the kerf length ranges from zero to ingot diameter and back to zero as the cut progresses. This requires variations in the workpiece loading to maintain the constant wire to workpiece loading ratio needed for a smooth, step free surface. In practice, an assortment of iron weights are added and removed by the operator every few minutes. This procedure yields a loading $\pm$ 10% of optimum which is sufficient for smooth

sawing. It does however require constant attention and it is a stepped rather than continuous adjustment. Design, calculations, and drawings for a simple mechanical device to constantly vary workpiece loading have been produced at Solarex. A basic sketch of the device is shown in Figure 1.

The quantity of wafers that can be sawn from a given length of silicon ingot is determined by the pitch of the wire guide rollers. Wire guide rollers with pitch of .4 millimeters are supplied by Yasunaga. These rollers yield a maximum area yield of wafer surface over gram/silicon of 10.8 cm^2g^{-1}. Solarex has designed and had constructed a chaser bit for grooving .3 millimeter wire guide rollers. These rollers carry more wire per unit of length and can give an area yield/gram of 14.3 cm^2g^{-1}.

Two sets of .3mm wire guide rollers were received from the machine shop, but poor detail and uneven grooves allowed lateral movement of wires across the web. The chaser bit was examined to determine the reason for the poor grooves. Under 20X magnification enough deformation of the teeth was noted to cause problems. The machine shop reworked the cutting edge of the tool and regrooved the two roller sets. One of these was much better, the other somewhat, but excellent uniformity still was not achieved.

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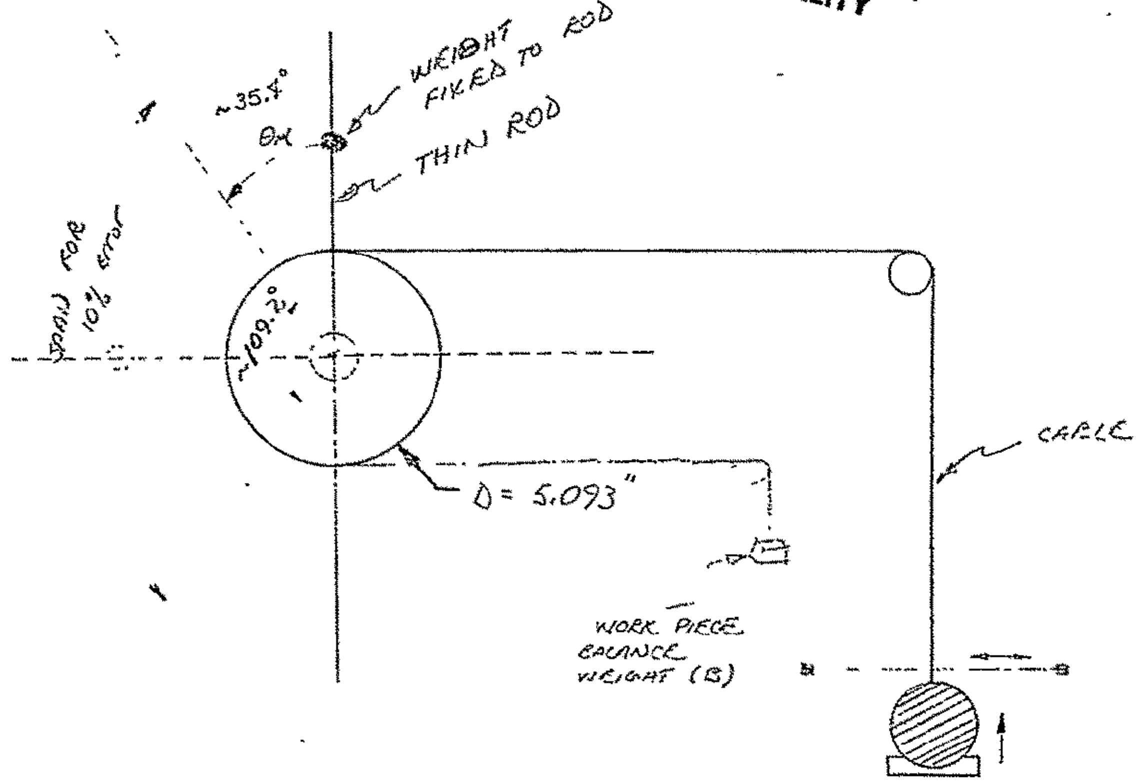

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	APPROVALS	DATE	
MATERIAL	DRAWN		FIGURE 1 DEVICE TO MAINTAIN CONSTANT WIRE TO WORKPIECE LOADING FOR YASUNAGA SAW
	CHECKED		SIZE A
FINISH			
DO NOT SCALE DRAWING			SCALE / SHEET / OF

It appears that the tool is not hardened enough for the fine teeth to hold up under the high frictional drag which occurs during regrooving. The bit was ordered, made from a prehardened steel (Rockwell #40) but this may not be the case. Three saw runs were carried out with these .3mm wire guide rollers; two were successful yielding 14.3 cm^2g^{-1}. The silicon surfaces were irregular and the wafers were of varying thicknesses. This can be attributed to the poor machine shop work; the tooling does, however, yield the substantially increased number of wafers expected. The machine shop was contacted and an appointment has been made to discuss the problem and find a solution.

An abrasive slurry is the actual cutting medium used with the Yasunaga wire saw. A silicon carbide grit is brought to bear against the silicon ingot by the steel wire. Experimental cuts made with the slurry recommended by Yasunaga have resulted in problems caused by the tendency of this grit to go out of suspension in the carrier medium. Due to the thinness of the #3 lapping oil and the high ratio of abrasive to oil, (3/2 by volume) settling occurs quickly, requiring that clean-up be performed immediately after the cut is finished. After overnight settling, 20 minutes

of stirring is required. During the cut, constant agitation is accomplished by a regulated aeration system included with the saw. Clogging of the pumping system sometimes results and may have contributed to the slurry delivery hose rupture that has occured once during this contract and a few times at Yasunaga in Japan. Separation and cleaning of the wafers is extremely difficult because of the adhesive quality of this type of slurry. Increased breakage results as well as the amount of post sawing damage from abrasive on the wafer surfaces.

Tests were made using different oils, mixtures of oils and abrasive concentrations. These experiments resulted in the selection of a special polishing compound oil and a 1/1 abrasive concentration. This oil is purchased from Process Research Company and is composed of thin base oils, surfacants, and clay platelets. The platelets greatly improve the suspension quality without any appreciable effect on the cutting characteristics or wafer surfaces. The consistency can be altered by adding various amounts of the #3 lapping vehicle. All of the aforementioned problems arising from abrasive settling are virtually eliminated. Major benefits resulting from the new slurry are as follows:

1. Cleaning of wafered slices and of the saw after each run is more thorough and involves 1/3 less time.
2. An expensive and fairly complicated air agitation system incorporated in the saw could be eliminated.
3. Sawn wafer yields are higher.
4. This slurry is less expensive unit for unit then the manufacturers' specified slurry.

Wafering Demonstration Runs

Six wafering parameters most directly affect the economics of cell preparation. Three are considered prime wafering variables directly affecting wafer thickness and kerf loss and their evaluation will be our first priority. They are "pitch", abrasive diameter, and wire size. The total area of solar cells produced per unit weight of ingot depends directly on the wire spacing or roller groove pitch. The difference in area of yield of wafers/Kg ingot as a function of pitch in the planned demonstration runs is as much as 2X. Cells fabricated with good Back Surface Fields can produce comparable cell efficiencies for thin cells and for thick; therefore, a small pitch can result in an appreciable photovoltaic power cost reduction. Three pitches, .3, .4 and .6 mm, four abrasive sizes, 5, 10, 15, and 30μ and four wire diameters, 3, 4, 6 and 8 mil are being used. Assuming a kerf width approximately equal to the wire diameter plus 3 times the abrasive diamter, various combinations of the above parameters might produce wafer/kerf ratios of from 0.026 to 5.56. The most promising combinations in terms of realistic dimensions and economic feasibility are being tested.

Of the secondary wafering parameters, wire feed rate is established by the strength of the wire. As the wire feeds through the kerfs in the ingot the abrasive slurry wears on the wire itself. Very high feed rates are required for

minimal strength wire sizes. Yasunaga recommends a relatively fast feed rate of about 10 meters per minute (less than 10% wire wear) for all wire sizes. In practice we have found that feed rates as low as 3 meters per minute are effective for relatively strong wire. Approximately seventy-five wafers are being cut per demonstration run. Runs yielding greater than 200 wafers each will be required to fully optimize the cost efficiency of the saw. Labor, machine time and wire usage will be almost the same for cutting a full size ingot as for a smaller ingot. Wire wear will be greater, however, and wire feed rates will have to be adjusted accordingly.

Wire speed is the rate at which the moving wires saw back and forth as a blade package. This speed impacts wire wear and cutting time. It may also affect the overall silicon surface topography; influencing the presence of wire works and ridges which are visible by eye.

This large scale surface topography is most influenced by wire loading; by the pressure with which the ingot is pressed through the cutting blades. Extremes of pressure cuase the blades to wander. The constant wire to workpiece loading device depicted in Figure 1 is designed to maintain pressure near this optimum.

A total of thirty sawing demonstration runs are tentatively planned. These were selected from the matrix of 48 possible combinations of wire diameter, abrasive size and roller ptich. Runs were chosen from the complete list by selecting those which would be most effective based upon calculated weight percent yields (grams wafer per gram ingot >33.9%, most yields are well above 50%, and by eliminating those calculated to yield an unrealistic (wafer < 4 mils thickness prior to etching or impractical wafer >15.8 mils) product. The runs planned are given in Table I. In all cases the silicon used for the demonstration runs will be 3 inch diameter, p-type, .5-2.0 ohm/cm single crystal. Fourteen sawing runs have been completed (Table II, Table III). Run #1 was terminated prematurely when the wire broke. The failure was due to excessive wire wear when the wire was cutting the plaster mounting block as well as the silicon. The wafers obtained from this run and from some other aborted runs are suitable for characterization and cell processing. Run #2 was a good cut, made with 15 micron abrasive. Run #3 was repeatedly bothered by a failure of the roller grooves to retain and guide the wires. In run #4.1, the 3 mil wire broke. In 4.2, the 4 mil wire was too thin, too lightly tensioned to remain tight through out the run. In run 4.3, as above, 4 mil with increased tension cut unevenly; it cut faster at the last kerfs, increasing workpiece pressure on those individual fast wires until the wire broke. Run #4.4 was a good cut due to stronger 6 mil wire; a fast cut due to larger

TABLE I

RUN NO.	WIRE (mil)	ABRASIVE (mm)	PITCH (mm)	CALCULATED (mil) Wafer	Kerf	CALCULATED Weight%Yield	AREA YIELD/gm
1	6	.030	.6	14.4	9.6	60	7.2cm^{2}g^{-1}
	3	.015	.4	10.9	4.8	69.4	10.8cm^{2}g^{-1}
	4	.015	.4	9.9	5.8	63	10.8cm^{2}g^{-1}
3	6	.015	.4	7.9	7.8	50.3	10.8cm^{2}g^{-1}
	3	.030	.4	9.2	6.5	58.6	10.8cm^{2}g^{-1}
	4	.030	.4	8.2	7.5	52.2	10.8cm^{2}g^{-1}
14	8	.005	.6	15.0	8.6	63.5	7.2cm^{2}g^{-1}
7	8	.010	.6	14.0	9.6	59.3	7.2cm^{2}g^{-1}
2	6	.015	.6	15.8	7.8	67	7.2cm^{2}g^{-1}
8	8	.015	.6	13.8	9.8	58.5	7.2cm^{2}g^{-1}
	8	.030	.6	12.1	11.5	51.3	7.2cm^{2}g^{-1}
	3	.005	.3	8.2	3.6	69.5	14.3cm^{2}g^{-1}
	4	.005	.3	7.2	4.6	61	14.3cm^{2}g^{-1}
	6	.005	.3	5.2	6.6	44.1	14.3cm^{2}g^{-1}
	3	.010	.3	10.2	4.6	68.9	14.3cm^{2}g^{-1}
	4	.010	.3	9.2	5.6	62.2	14.3cm^{2}g^{-1}
11	6	.010	.3	7.2	7.6	48.6	14.3cm^{2}g^{-1}
	8	.010	.3	5.2	9.6	35.1	14.3cm^{2}g^{-1}
	3	.015	.3	7.0	4.8	59.3	14.3cm^{2}g^{-1}
	4	.015	.3	6.0	5.8	50.8	14.3cm^{2}g^{-1}
10	6	.015	.3	4.0	7.8	33.9	14.3cm^{2}g^{-1}
	3	0.30	.3	5.3	6.5	44.9	14.3cm^{2}g^{-1}
	4	0.30	.3	4.3	7.5	36.4	14.3cm^{2}g^{-1}
	3	.005	.4	12.1	3.6	77.1	10.8cm^{2}g^{-1}
	4	.005	.4	11.1	4.6	70.1	10.8cm^{2}g^{-1}
12	6	.005	.4	9.1	6.6	58	10.8cm^{2}g^{-1}

TABLE I CONTINUED

	WIRE (mil)	ABRASIVE (mm)	PITCH (mm)	CALCULATED(mil) Wafer	Kerf	CALCULATED Weight%Yield	AREA YIELD/gm
13	8	.005	.4	7.1	8.6	45.2	10.8cm^{2}g^{-1}
	3	.010	.4	11.1	4.6	70.1	10.8cm^{2}g^{-1}
	4	.010	.4	10.1	5.6	64.3	10.8cm^{2}g^{-1}
5	6	.010	.4	8.1	7.6	51.6	10.8cm^{2}g^{-1}
6	8	.010	.4	6.1	9.6	38.9	10.8cm^{2}g^{-1}
9	8	.015	.4	6.0	9.8	62.0	10.8cm^{2}g^{-1}
4	6	.020	.4	7.4	8.4	53.2	10.8cm^{2}g^{-1}

TABLE II

PITCH	.3 mm	Run #	10 11
	.4 mm		3 4 5 6 7 9 12 13
	.6 mm		1 2 8 14
WIRE DIAM.	6 mm	Run #	1 2 3 4 5 10 11 12
	8 mm		6 7 8 9 13 14
GRIT SIZE	.005 mm	Run #	12 13 14
	.010 mm		5 6 7 11
	.015 mm		2 3 8 9 10
	.030 mm		1

Wafering Variables - Demonstration Runs Completed

TABLE III COMPLETED WAFERING DEMONSTRATION RUNS

SPECIFICATION OF PROSPECT

		#1	#2	#3
1.	Material	Silicon	Silicon	Silicon
2.	Dimensions	80x82mm	80x71mm	80x69mm
3.	Machine No.	1	1	1

CUTTING CONDITIONS

		#1	#2	#3
1.	No. Wires	75	75	75
2.	Roller Pitch	.6mm	.6mm	.4mm
3.	Wire Dia. (mil)	6	6	6
4.	Type	XLO Music	XLO Music	XLO Music
5.	Strength (kg)	∿5.1	∿5.1	∿5.1
6.	Tension (kg)	1.3	1.6	1.6
7.	Cycle Rate (cpm)	50-55	50-55	55-60
8.	Feed Rate (mpm)	9.6	5-6	6
9.	Wire Wear (mil)	.1-.4	∿.5	5.7
10.	Wire Used (M)	5500	3400	5610
11.	Wire Used (kg)	.78	.429	.80
12.	Abrasive Size/Type	SiCμ30	15μSiC	15μSiC
13.	Suspension Medium	#3 Oil	#3 Oil	#3 Oil
14.	Prior Use	No	0	1
15.	12/13	3/2	3/2	3/2
16.	Mean Weight gm/cm	20	20	20
17.	Total Weight (kg)	6-11.5	6-11.5	12.0
18.	Av. Kerf Length	6.94mm	6.94mm	6.94mm
19.	Bond	DeKhotinsky	DeKhotinsky	DeKhotinsky

WORKING EFFICIENCY

		#1	#2	#3
1.	Working Time	13hr, 40 min.	10hr, 20 min,	9hr, 35 min.
2.	Yield Unbroken/Total	73/74	71/75	65/75
3.	Time of Unit Work	11.08min	8.73min	8.89min
4.	Total Area Cut (cm^2)	3375	3375	3375
5.	Kerf Volume per Wire (cm^3)	1.1	0.89	0.89

TABLE III COMPLETED WAFERING DEMONSTRATION RUNS

SPECIFICATION OF PROSPECT	#4.1	#4.2	#4.3	#4.4	#5	#6
1. Material	Silicon	Silicon	Silicon	Silicon	Silicon	Silicon
2. Dimensions	80x50	80x50	80x50	60x60	70x50	60x45
3. Machine No.	YQ100	YQ100	YQ100	YQ100	YQ100	YQ100
<u>CUTTING CONDITIONS</u>						
1. No. Wires	75	75	75	75	75	76
2. Roller Pitch	.4mm & .6mm	.4mm	.6	.4	.4mm	.4
3. Wire Dia. (mil)	3	4	4	6	6	8
4. Type	XLO Music	XLO Music	XLO Music	XLO Music	XLO Music	XLO Music
5. Strength (kg)	3.0	1.8	1.8	5.1	5.1	approx. 9.0
6. Tension (kg)	.32,.39,.48,.6	.65	.7	1.6	1.6	2.5
7. Cycle Rate (cpm)	55	55-60	55-60	55-60	65	65
8. Feed Rate (mpm)	8	8-6	6-8	6-7	6	5-6
9. Wire Wear (mil)				5.7	5.7	.1-.5
10. Wire Used (M)				1920	3510	
11. Wire Used (kg)				.27	.5	
12. Abrasive Size/Type	15µSiC	15µSiC	15µSiC	20µSiC	10µSiC	10µSiC
13. Suspension Medium	#3 oil	#3 oil	#3 oil	#3 oil	#3 oil	#3 oil
14. Prior Use	1	2	3	0	0	1
15. 12/13	3/2	3/2	3/2	3/2	3/2	3/2
16. Mean Weight gm/cm	20	20	20	20	20	20
17. Total Weight (kg)	12.0 max	12.0 max	12.0 max	12.0 max	12.0 max	12.0 max
18. Av. Kerf Length	6.94mm	6.94mm	6.94mm	6.94mm	6.94mm	6.94mm
19. Bond	Dop wax	Hot melt wax	Dop wax	Dop wax	Dop wax	Dop wax
<u>WORKING EFFICIENCY</u>						
1. Working Time	run prematurely	run prematurely	run prematurely	5hr. 20min.	9hr. 45 min.	11:15
2. Yield Unbroken/Total	failed	failed	failed	73/75	75/75	72/74
3. Time of Unit Work	wire	wire	wire	.073 hrs.	.130 hrs.	.156 hrs.
4. Total Area Cut (cm^2)	broke	broke	broke	2092	2848	2121
5. Kerf Volume per Wire (cm^3)				.593	.693	.650

TABLE III COMPLETED WAFERING DEMONSTRATION RUNS

SPECIFICATION OF PROSPECT				DEMONSTRATION		
	#7	#8.1	#8.2	#8.3	#8.4	#9
1. Material	Silicon	Silicon	Silicon	Silicon	Silicon	Silicon
2. Dimensions	65x55	75x45	75x45	75x50	80x45	65x35
3. Machine No.	YQ100	YQ100	YQ100	YQ100	YQ100	YQ100
CUTTINGCONDITIONS						
1. No. Wires	75	75	75	75	75	75
2. Roller Pitch	.6mm	.4	.4	.4	.6	.4
3. Wire Dia. (mil)	8	4	4	4	8	8
4. Type	XLO Music	XLO High Carbon	XLO High Carbon	XLO High Carbon	XLO Music	XLO Music
5. Strength (kg)	approx. 9.0	2.7	2.7	2.7	9	9
6. Tension (kg)	2.5	1.5	1.4	1.4	2.9	2.5
7. Cycle Rate (cpm)	65	65	65	65	65	65
8. Feed Rate (mpm)	5	8	8	8	5-6	5-6
9. Wire Wear (mil)	.1-.4		N/A	N/A	.6	.6
10. Wire Used (M)			N/A	N/A		
11. Wire Used (kg)						
12. Abrasive Size/Type	10µSiC	15µSiC	15µSiC	15µSiC	15µSiC	15µSiC
13. Suspension Medium	#3 oil	# 3 oil	#3 oil	#3 oil	# 3 oil	# 3 oil
14. Prior Use	2	0	0	0	1	2
15. 12/13	3/2	3/2	3/2	3/2	3/2	3/2
16. Mean Weight gm/cm	20	20-21 max	20 max	20 max	20-21 max	20-21.5 max
17. Total Weight (kg)	12.0 max	12.0 max	12.0 max	12.0 max	12.0 max	12.0
18. Av. Kerf Length	6.94mm	7	7	7	7	7
19. Bond	Dop wax	Dop Wax	Dop Wax	Dop Wax	Dop Wax	Dop Wax
WORKING EFFICIENCY						
1. Working Time	12:07		Spool	Spool	9 HR 40 min.	7 HR 30 min.
2. Yield Unbroken/Total	73/74	Spool	Cracked	Bending	74/74	73/74
3. Time of Unit Work	.166 hrs.	Broken	Run	Wire	.132 hrs.	.102 hrs.
4. Total Area Cut (cm^2)	2456	Run	Aborted	Tangled	3717	2454
5. Kerf Volume per Wire (cm^3)	.763	Aborted		Run Aborted	1-22	.846

TABLE III COMPLETED WAFERING DEMONSTRATION RUNS

SPECIFICATION OF PROSPECT	#10.1	#10.2	#11	#12	#13.1	#13.2
1. Material	Silicon	Silicon	Silicon	Silicon	Silicon	Silicon
2. Dimensions (mm)	65 x 40	70 x 40	70 x 35	65 x 45	65 x 45	60 x 50
3. Machine No.	YQ100	YQ100	YQ100	YQ100	YQ100	YQ100
<u>CUTTING CONDITIONS</u>						
1. No. Wires	116	116	80	75	75	75
2. Roller Pitch (mm)	.3	.3	.3	.4	.4	.4
3. Wire Dia. (mil)	6	6	6	6	8	8
4. Type	XLO Music	XLO Music	XLO Music	XLO Music	XLO Music	XLO Music
5. Strength (kg)	5.1	5.1	5.1	2.5	9.0	9.0
6. Tension (kg)	1.6	1.6	1.6	1.6	2.5	2.5
7. Cycle Rate (cpm)	65	65	65	4.5	3	60-65
8. Feed Rate (mpm)	5	6	5	.3	.5	3
9. Wire Wear (mil)	.3	.25	.4	.3	.5	.5
10. Wire Used (M)	N/A	3298	2220	2924	N/A	2034
11. Wire Used (kg)	N/A	.471	.317	.417	N/A	.29
12. Abrasive Size/Type	15uSiC	15uSiC	10uSiC	5uSiC	5uSiC	5uSic
13. Suspension Medium	#3 LAP oil	#3 LAP oil	#3 LAP oil	#3 LAP oil	#3 LAP oil	#3 LAP oil
14. Prior Use	3	0	0	0	1	2
15. 12/13	3/2	3/2	3/2	3/2	3/2	3/2
16. Mean Weight gm/cm	20 max	18-19 max	18-20 max	20 max	20 max	20.0 max
17. Total Weight (kg)	19.0	17.5	13.0	12.0	12.0	12.0
18. Av. Kerf Length	6.94	6.94	6.94	6.94	6.94	6.94
19. Bond	Dop Wax	Dop Wax	Dop Wax	Dop Wax	Dop Wax	Dop Wax
<u>WORKING EFFICIENCY</u>						
1. Working Time	Run Failed	9 hr 10 min	7 hr 25 min	10 hr 50 min	Run Failed	11 hr 18 min
2. Yield Unbroken/Total	N/A	100/115	75/79	74/74	N/A	73/74
3. Time of Unit Work	N/A	.0916	.0986	.146	N/A	.155
4. Total Area Cut (cm^2)	N/A	3846	2884	2846	N/A	2091
5. Kerf Volume per		.788	.703	.547	N/A	.574
Wire (cm^3)	N/A				N/A	

TABLE III COMPLETED WAFERING DEMONSTRATION RUNS

SPECIFICATION OF PROSPECT	#14
1. Material	Silicon
2. Dimensions	60x50
3. Machine No.	YQ-100

CUTTING CONDITIONS

1. No. Wires	75
2. Roller Pitch	.4
3. Wire Dia. (mil)	8
4. Type	XLO Music
5. Strength (kg)	$\sim$9.0
6. Tension (kg)	$\sim$2.5
7. Cycle Rate (cpm)	60-65
8. Feed Rate (mpm)	3
9. Wire Wear (mil)	.5
10. Wire Used (M)	2966
11. Wire Used (kg)	.847
12. Abrasive Size/Type	5 SiC
13. Suspension Medium	#3 Oil
14. Prior Use	2
15. 12/13	3/2
16. Mean Weight gm/cm	18 max
17. Total Weight (kg)	12.0
18. Av. Kerf Length	
19. Bond	Dop Wax

WORKING EFFICIENCY

1. Working Time	16hr. 25 min.
2. Yield Unbroken/Total	73/74
3. Time of Unit Work	.225
4. Total Area Cut (cm^2)	2062
5. Kerf Volume per Wire (cm^3)	1.40

abrasive. Run #5 was similar to #4.4 with a smaller grit size. Run #6 with strong 8 mil wire was a good cut. Run #7 was similar to #6, with a different pitch, a good cut. Run #8.1 utilized a stronger and more elastic high carbon steel wire which over tensioned and compressed the spool during the run. Run 8.2, as 8.1 with reduced winding tension on spool, cracked the aluminum hub and sprung the steel rim out of round. Run #8.3 was similar to 8.1, 8.2. Run 8.4 was a good cut, similar to #6 and #7, stonger 8 mil wire was used. Run #9 was similar to #8.4, #7, #6 with fine .4mm pitch; a good cut. Run #10.1 used very fine .3 mm pitch wire guide rollers. The roller grooving tool deformed in operation. The rollers therefore, were not accurately cut. In cutting, wires jumped out of and across grooves. The run was aborted. Run 10.2 was similar to 10.1; it was marginally sucessful. The implication is that with good tooling area yield/gram of $14.3 cm^2 g^{-1}$ is possible. Run 11 was similar to 10.1 and 10.2. Run 12 was cut with 5 micron SiC grit - a very fine grit. Cutting time was almost twice as long. Run 13.1 failed when the wax adhesive released the ingot from the mounting block. Run 13.2 was a good run, similar to 13.1, a slurry hose blockage occured and was repaired. Run 14 was a 5 micron grit cut. The cut was very slow since the fine grit had been used before and the slurry was saturated with silicon.

Wire Diameter

Run #4.1, 2, 3, and 4 show an increase in the wire diameter and strength used until the minimum reliable wire diameter was found. 6 mil wire seems to be the finest diameter which will be reliable for cuts involving large numbers of wafers and concurrent increase in drag over these test runs of 75 wafers. Runs 5 and 6 carry out tests with strong 6 and 8 mil wire to a higher degree of reliability. Run series 8.1, 2, 3 attempted to reduce the reliable operating minimum thickness wire to a strong, high carbon steel, 4 mil wire. This high carbon wire is so elastic that all spools failed from wire compression.

Pitch

Runs 1-10 utilized standard Yasunaga .4 and .6mm pitch rollers. The yield surface area/gram silicon is controlled by pitch - the number of grooves or wires per unit length. We increased this yield from the .6mm yield to the .4mm with no loss of reliability of saw operation. Run series 10 and 11 utilized a prototype .3mm wire spacing. Results were marginal due to poor tooling; however, we feel that the increased yields from this pitch are practical.

Abrasive Size

Runs 12 thru 14 utilized a very fine 5 micron silicon carbide abrasive in the saw cutting slurry. Earlier runs had used 10, 15 and 30 micron abrasive. Visible silicon surface textures

resulting from these grit sizes are depicted in Figures 2 through 4. (Overexposed photograph center area is an artifact of microscope lighting.) Surface damage is, as expected, greater for larger grit sizes. The effect of these variations will not be obvious until all Cell Processing Runs have been completed and electrically evaluated. In general, cutting time is the crucial variable involving abrasive size. Cutting time is inversely proportional to abrasive size. The cutting time for some of the 5 micron grit wafering runs was almost twice that of the coarse grit run. The effective lifetime or number of cuts possible with a single slurry mix, seems to be less for 5 micron slurry than for coarse slurry. The economic impact of these facts is totally dependent on cell electrical performance versus abrasive grit size.

It seems probable that any silicon surface damage occuring in sawing from abrasive, or other sources, may be removed by chemically polishing or etching. See Figures 5 through 10. Figures 5 through 10 depict silicon wafer surfaces with various quantities of silicon surfaces (or work damage) removed with a chemical etch. (Quantities stated, eg. 10 microns Si removed, means 1/2 that quantity removed from each wafer surface.) (Overexposed photograph center area is an artifact of microscope lighting.) Surfaces as sawn are very irregular; removal of increasing amounts of silicon with the ASTM Standard polishing etch (5:10:14 HNO_3:HF:CH_3COOH) yields an increasingly polished surface.

The surfaces themselves are depicted here; the effect of these surfaces will be further discussed in the section on Cell Processing, electrical evaluation; and in Figures 16 and 17.

Wire Sawn Silicon Surface
(all scales equal)
(375X)

Figure 2

10 micron SiC Abrasive

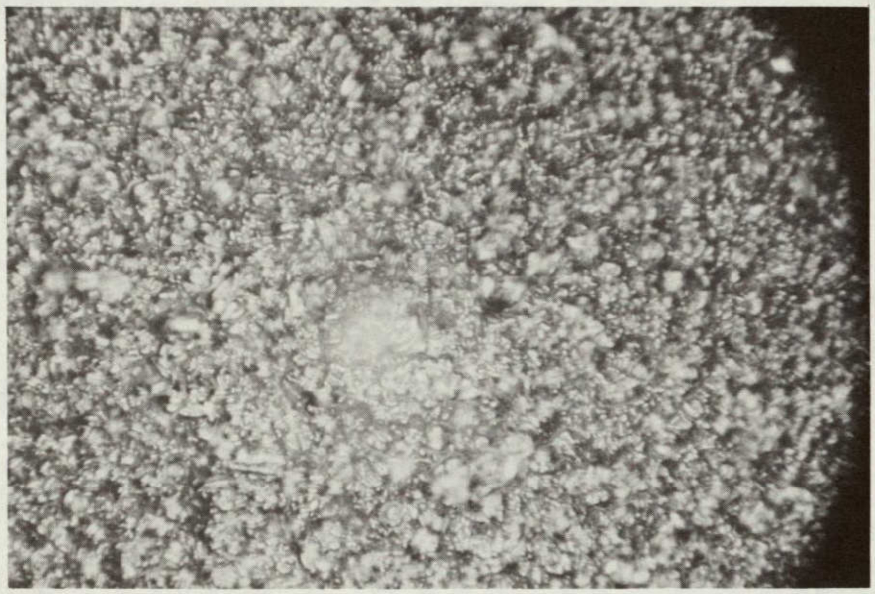


Figure 3

15 micron SiC Abrasive

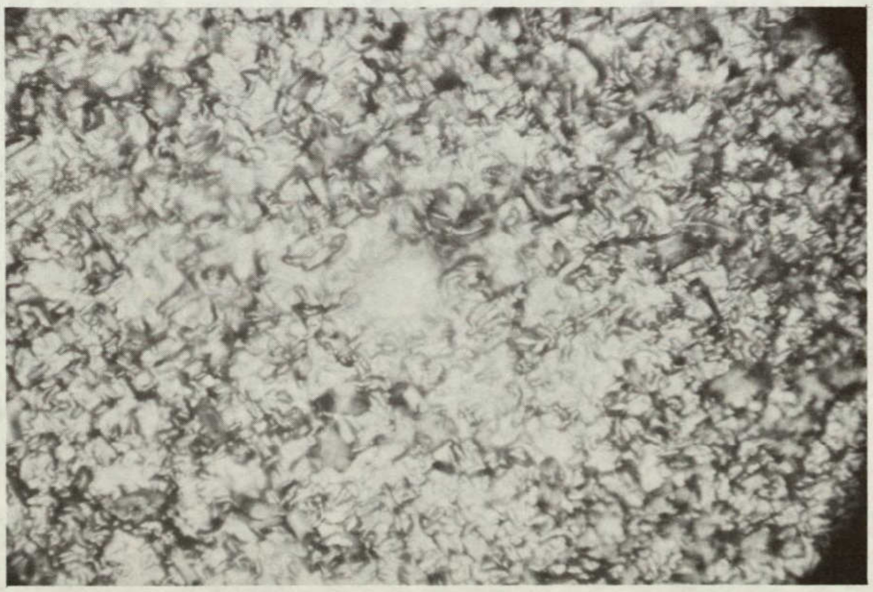


Figure 4

30 micron SiC Abrasive

Wire Sawn Silicon Surface
(all scales equal)
(375X)

ORIGINAL PAGE IS
OF POOR QUALITY

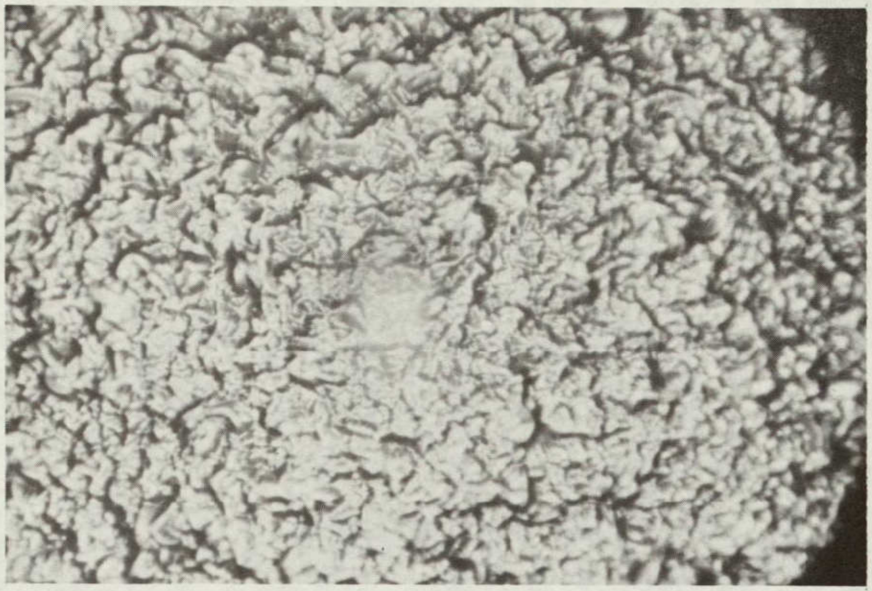


Figure 5

5 microns Si removed

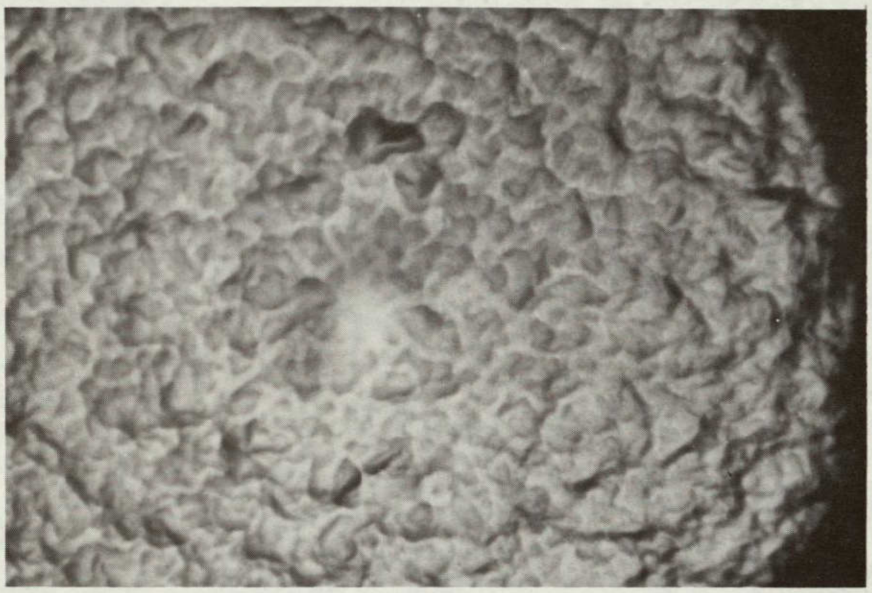


Figure 6

10 microns Si removed

Figure 7

15 microns Si removed

Wire Sawn Silicon Surface
(all scales equal)
(375X)

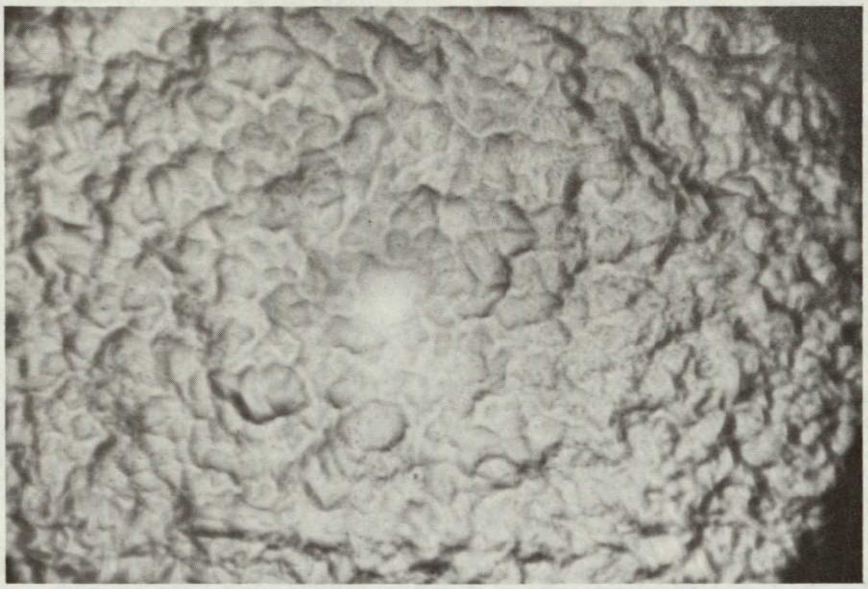


Figure 8

20 microns Si removed

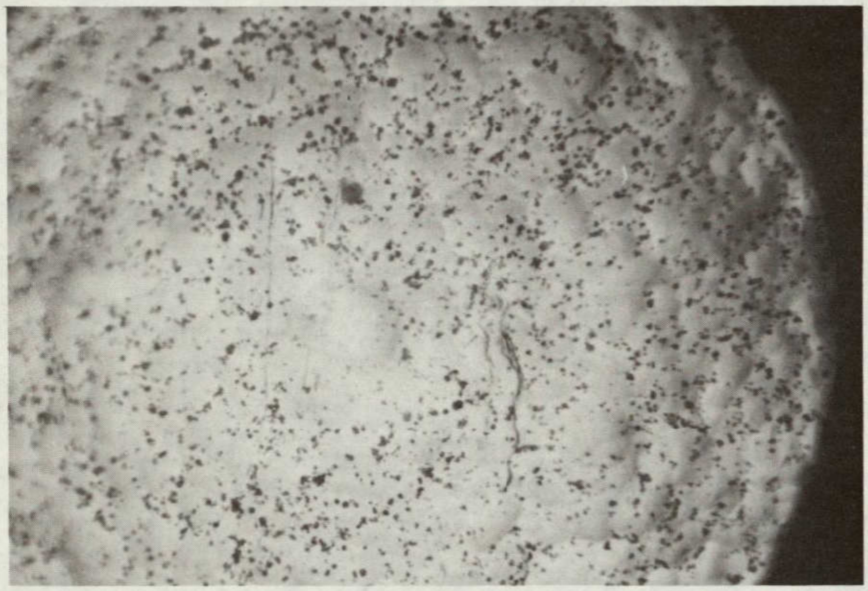


Figure 9

> 2 microns Si removed
(dark areas are dust particles)

Figure 10

> 50 microns Si removed

Wafer Thickness

Thickness measurements have been made for a representative lot of sawn wafers (WS-8.3). 20 full size wafers were measured (27% of the lot).

Minimum Thickness (in lot of 20)	348μ
Maximum Thickness (in lot of 20)	372μ

Thickness variation across the surface of the individual wafer average 12 microns. The individual wafer thickness variations occur in a pattern, the center of the wafer tends to be thicker, the edges thinner. In some cases the thick center area is displaced toward one edge, These variations in thickness are within Yasunaga specifications and are not detrimental to wafer processing.

Processing of ultrathin silicon requires minimal variations in thickness within a lot of wafers and minimal variation in thickness from edge to edge on the individual wafer. Two mil (Ultrathin) Silicon Wafers have been produced using wafers from WS-8.3. Wafers from this lot were 14 mils thick, the thickness variation is mentioned above. A solution of 25% Sodium Hydroxide at 105°C was the etchant. Wafers were etched to 2 mils (50μ ± 14μ).

Cell Processing Demonstration Runs

Cell processing runs have been initiated for sample quantities of those wafers cut in the saw demonstration runs in Table III. The demonstration cell processing sequence which is being carried out is depicted in Figure 11. Cells will be evaluated for any variations in processing requirements required by the various as sawn and etched surfaces. In general it has been observed that as sawn surfaces and those with little (<15 microns) silicon removed require processing adjustments to cope with the matte or textured surface. The only process change necessary is in photolithography - where additional photoresist thickness, is necessary to fully cover the textured silicon with photoresist. This, of course, implies concurrent adjustments in other steps in this photolithography process. This process variation does not effect processing times and throughput for whole lots.

Cell Processing Demonstration Runs 1 through 4 will be evaluated for electrical performance. The designations given in Table III for Wafering Demonstration Runs will be carried for Cell Processing Runs. Only the first four of these cell processing runs have been completed and tested to this date. Already, we have seen trends in electrical performance versus silicon surface preparation which should hold true. Lots numbered Wire Saw 1 thru Wire Saw 4 have

cell electrical characteristics graphed in Figures 12-1 thru 15-3. It will be seen that each Figure number representing a Wire Saw Lot has thru subnumbers -1 Cell Efficiency, -2 Short Circuit Current, -3 Fill Factor.

The effect of the silicon texturing visible in Figures 2 thru 10 is evidenced in enhanced light trapping and increased Isc for cells processed on this textured silicon. Spectrophotometer curves are presented in Figure 16 for the extreme cases of as sawn; > 50 microns of silicon removed. This depiction is for non antireflective coated silicon. Processed cell samples are coated with antireflective Ta_2O_5 which reduces the percentage enhancement of matte or textured surfaces over highly etched, chemically polished surfaces.

The effect of this light trapping, for cells which have some saw damage remaining on the silicon surface, is to compensate for diminished voltage and fill factor by enhancing current. This results in power maximums for cells with as little as 5 microns of silicon removed equaling Pmax for those with 15 or more microns removed. I/V curves for cells exhibiting this effect are shown in Figure 17.

FIG. 11 DEMONSTRATION CELL PROCESSING SEQUENCE

WAFERING

↓

CLEANING

↓

DIFFUSION
GASEOUS SOURCE

↓

VACUUM EVAPORATE
Al AT THE BACK

↓

p+ FORMATION
"ALLOYING"

↓

BACK EVAPORATION

↓

FRONT PATTERN DEFINITION
BY PHOTOLITHOGRAPHY

↓

FRONT EVAPORATION

↓

Ta_2O_5 AR COATING

↓

TEST

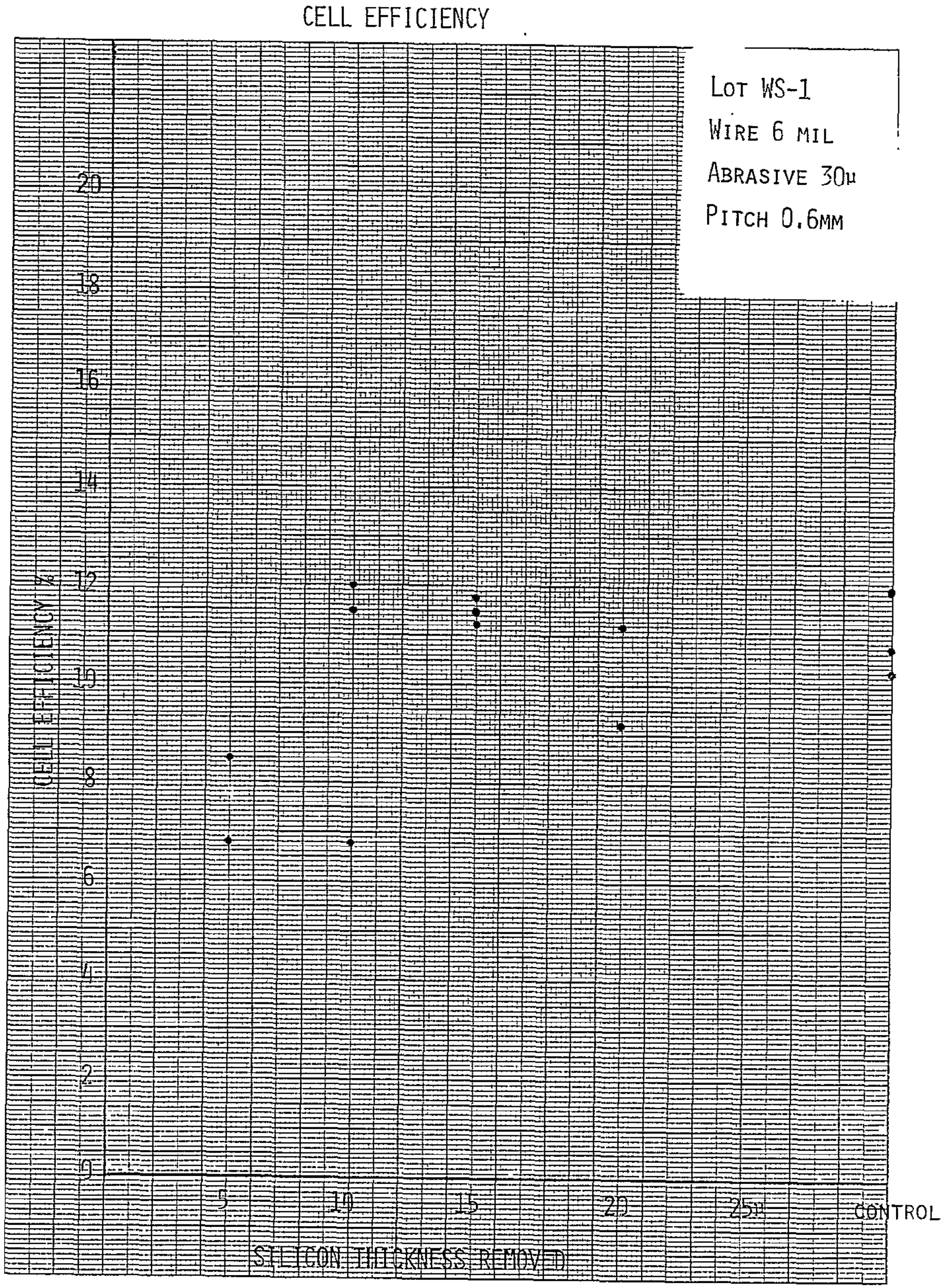

CELL EFFICIENCY
Lot WS-1
Wire 6 mil
Abrasive 30μ
Pitch 0.6mm
CELL EFFICIENCY %
20
18
16
14
12
10
8
6
4
2
0
5
10
15
20
25μ
CONTROL
SILICON THICKNESS REMOVED

Figure 12-1

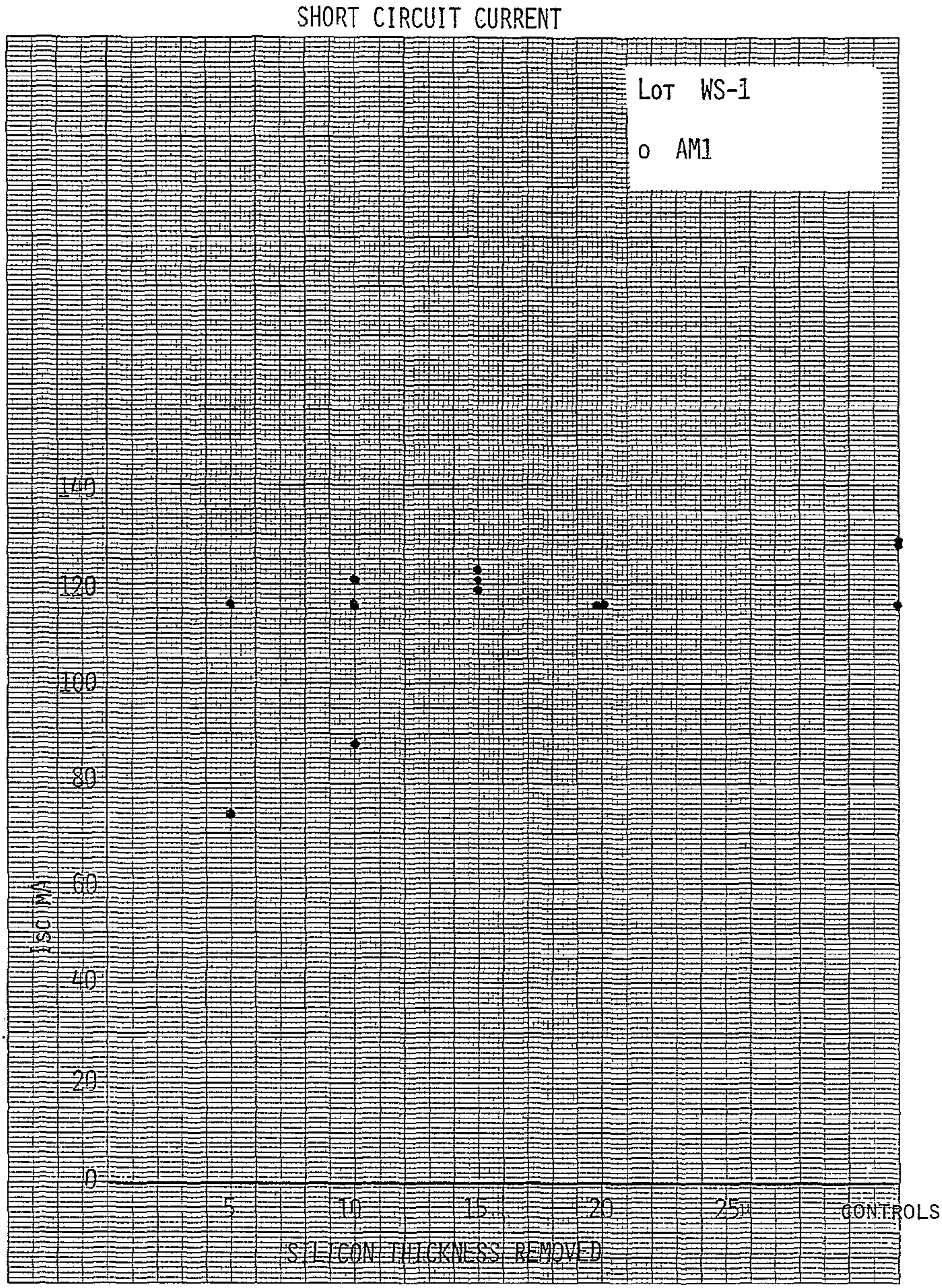

SHORT CIRCUIT CURRENT
LOT WS-1
o AM1
ISC MA
140
120
100
80
60
40
20
0
5
10
15
20
25μ
CONTROLS
SILICON THICKNESS REMOVED

Figure 12-2

FILL FACTOR

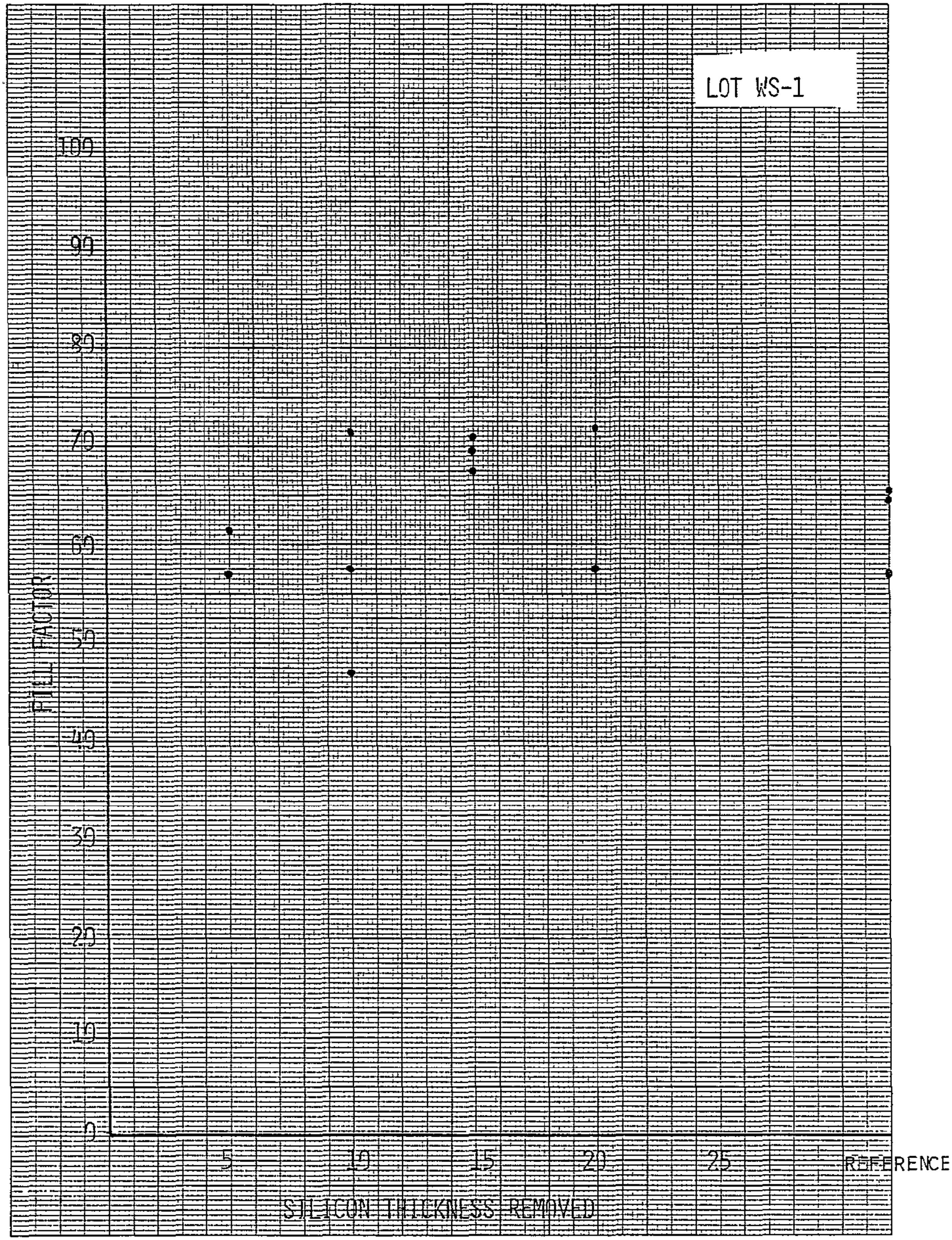


Figure 12-3

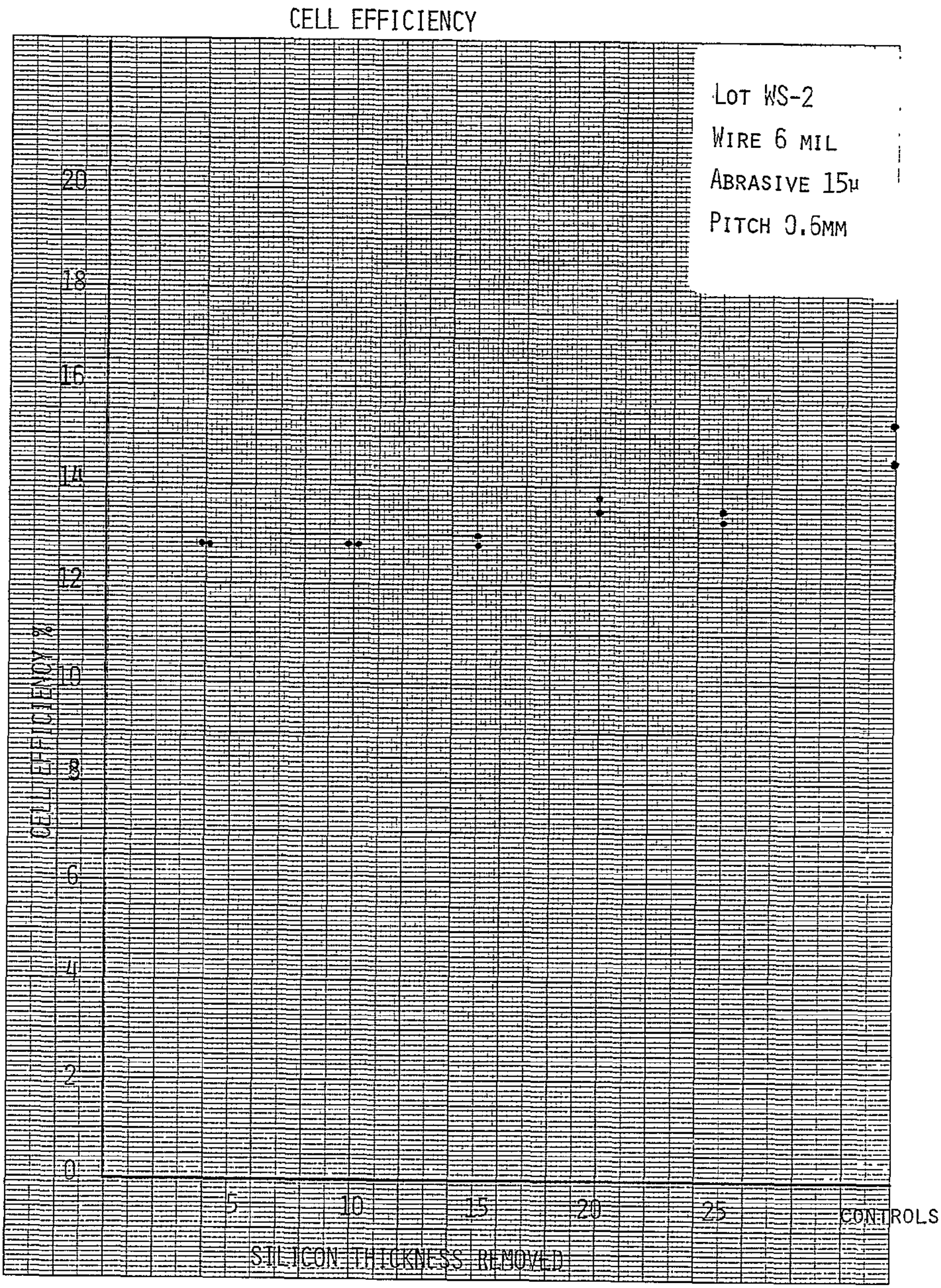

CELL EFFICIENCY
Lot WS-2
Wire 6 mil
Abrasive 15μ
Pitch 0.6mm
CELL EFFICIENCY %
20
18
16
14
12
10
8
6
4
2
0
5
10
15
20
25
CONTROLS
SILICON THICKNESS REMOVED

Figure 13-1

SHORT CIRCUIT CURRENT

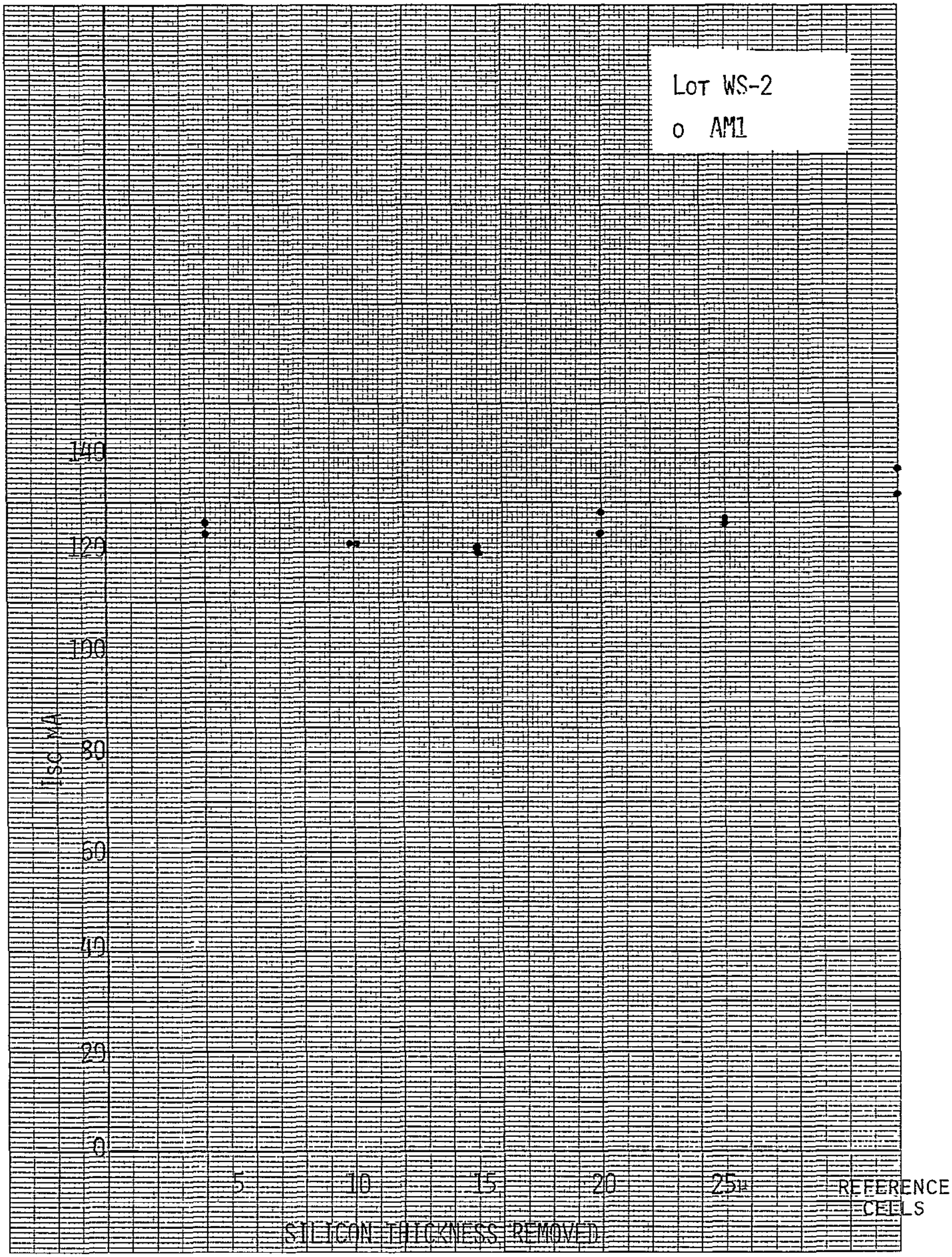
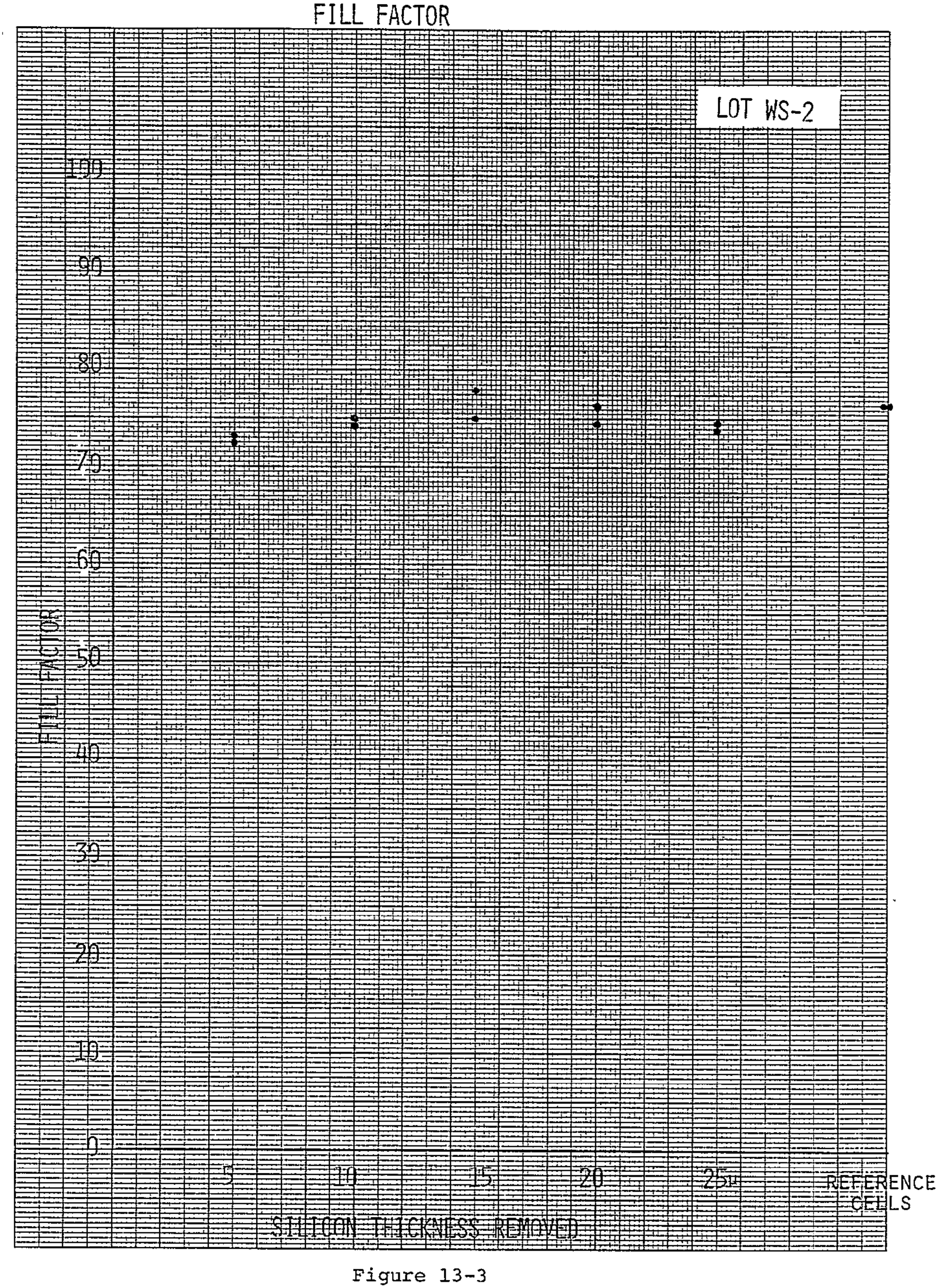


Figure 13-2



FILL FACTOR
LOT WS-2
100
90
80
70
60
50
40
30
20
10
0
FILL FACTOR
5
10
15
20
25μ
REFERENCE CELLS
SILICON THICKNESS REMOVED

Figure 13-3

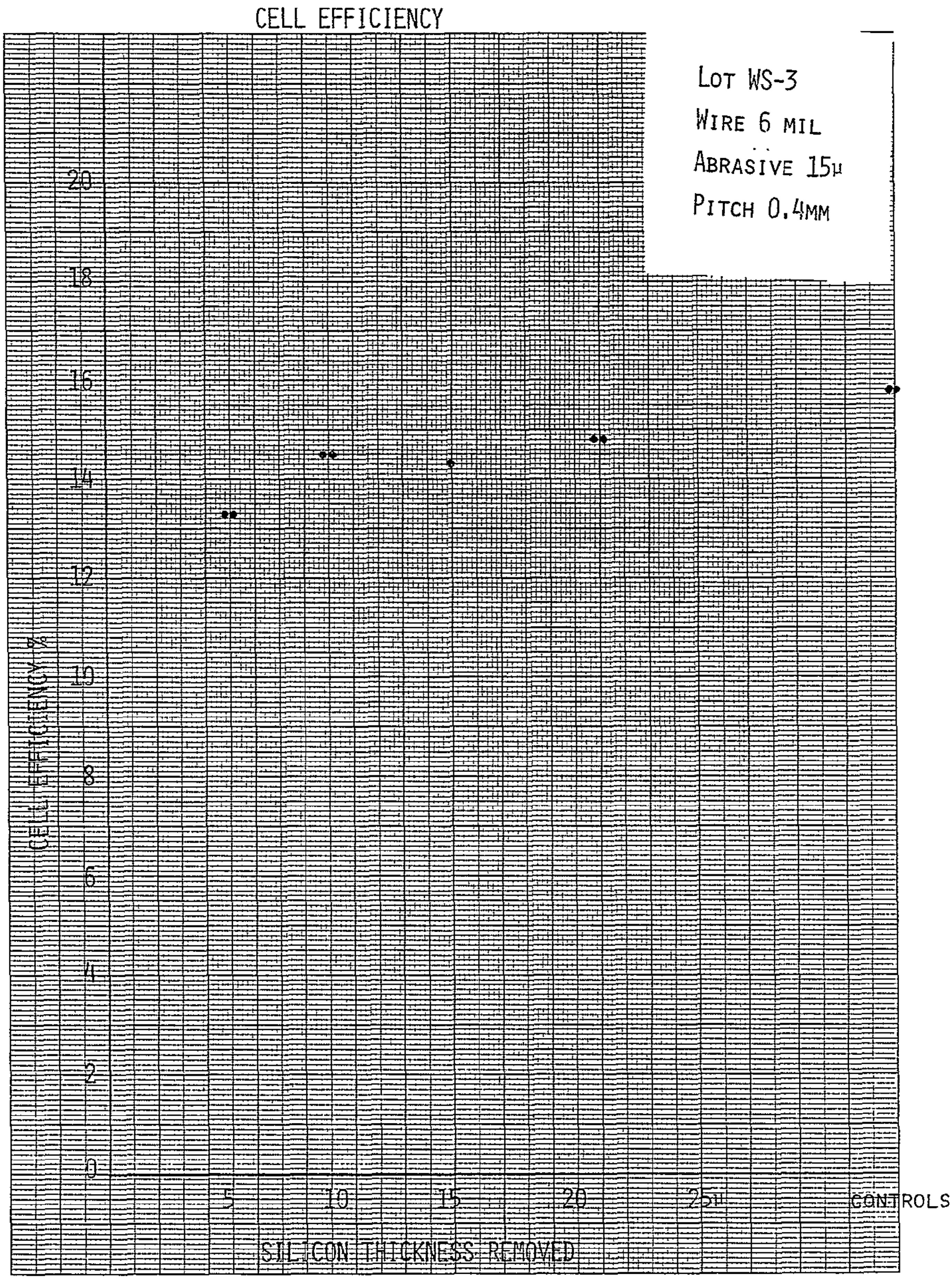

CELL EFFICIENCY
LOT WS-3
WIRE 6 MIL
ABRASIVE 15μ
PITCH 0.4MM
CELL EFFICIENCY %
20
18
16
14
12
10
8
6
4
2
0
5
10
15
20
25μ
CONTROLS
SILICON THICKNESS REMOVED

Figure 14-1

SHORT CIRCUIT CURRENT

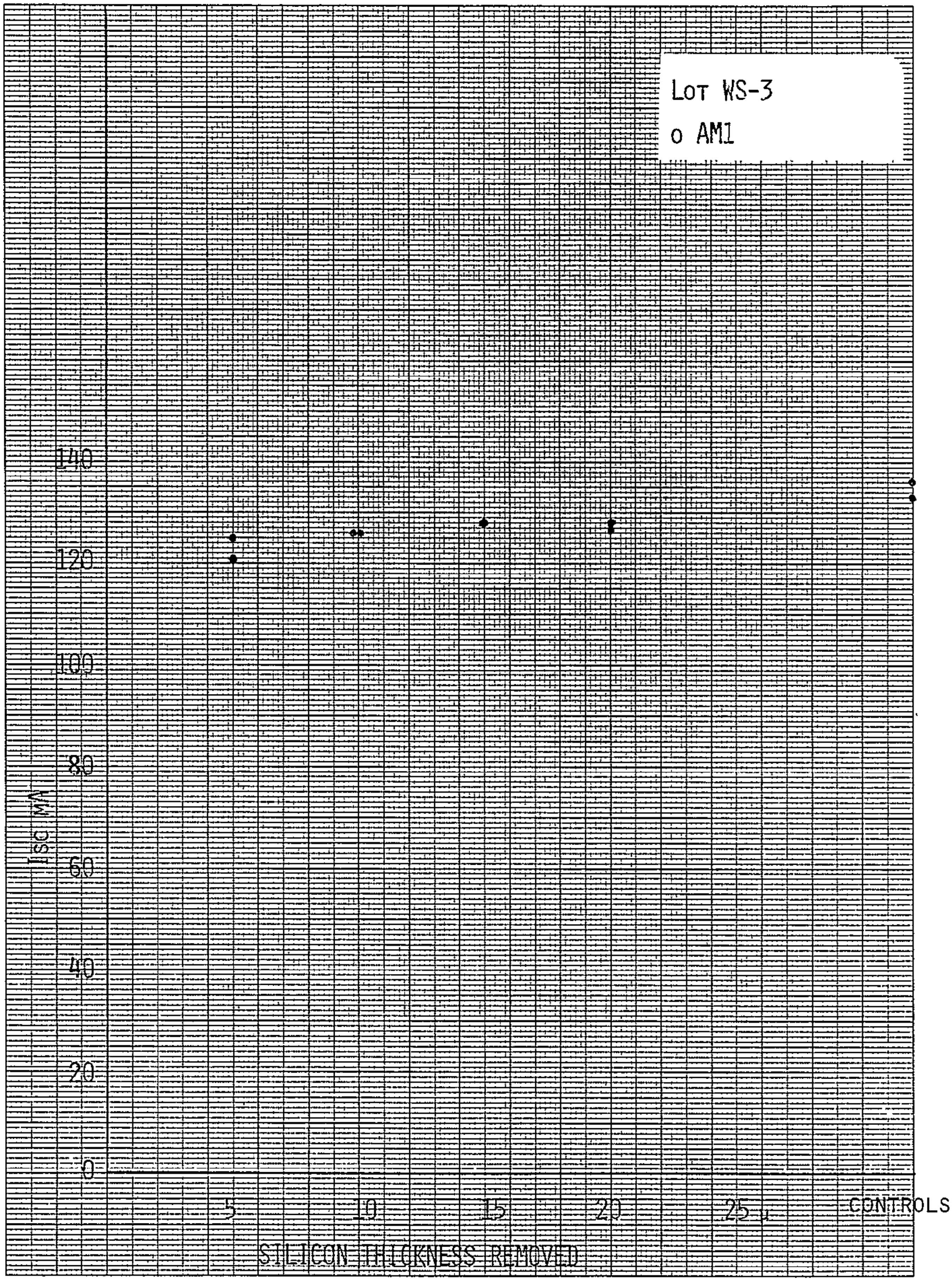


Figure 14-2

FILL FACTOR

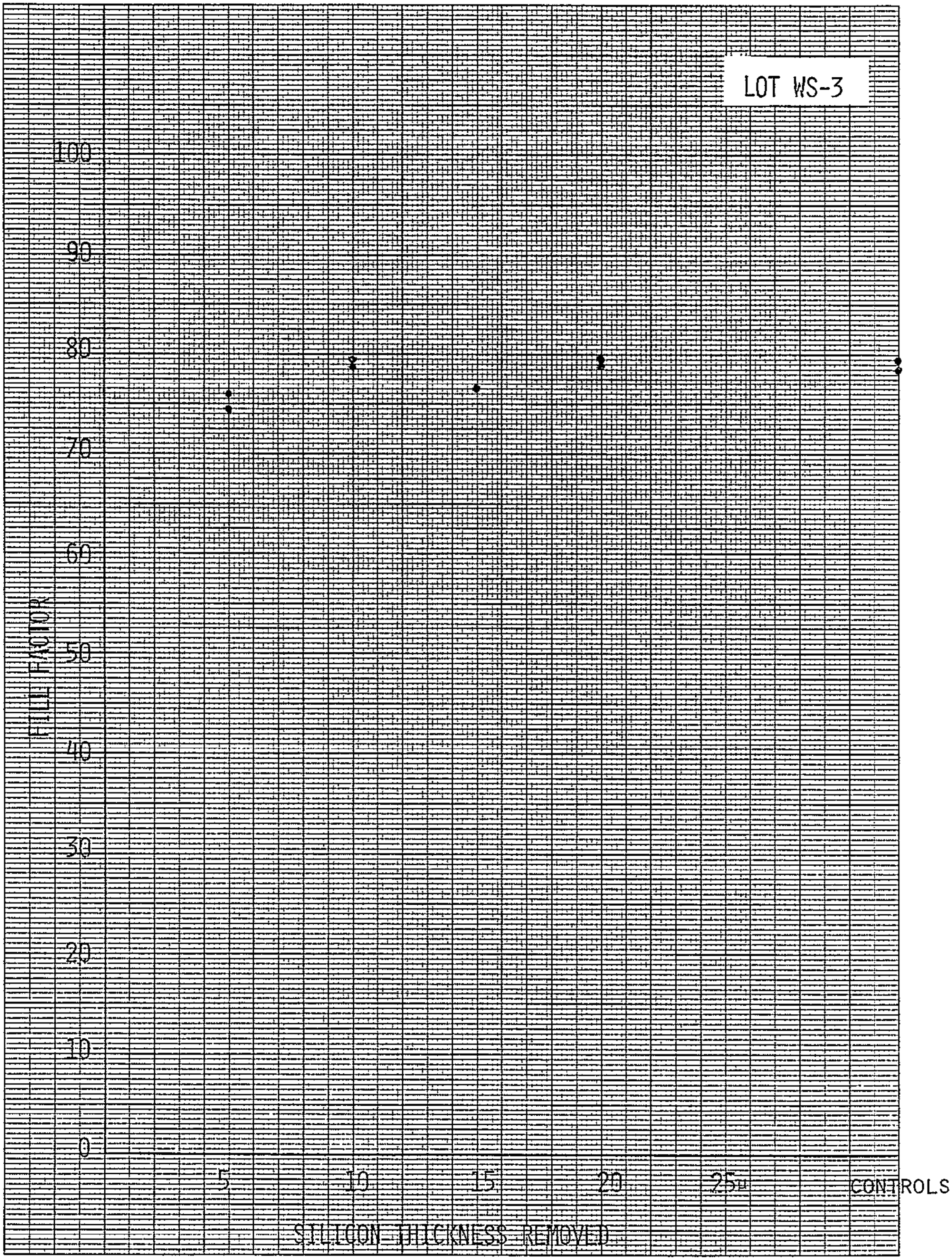


Figure 14-3

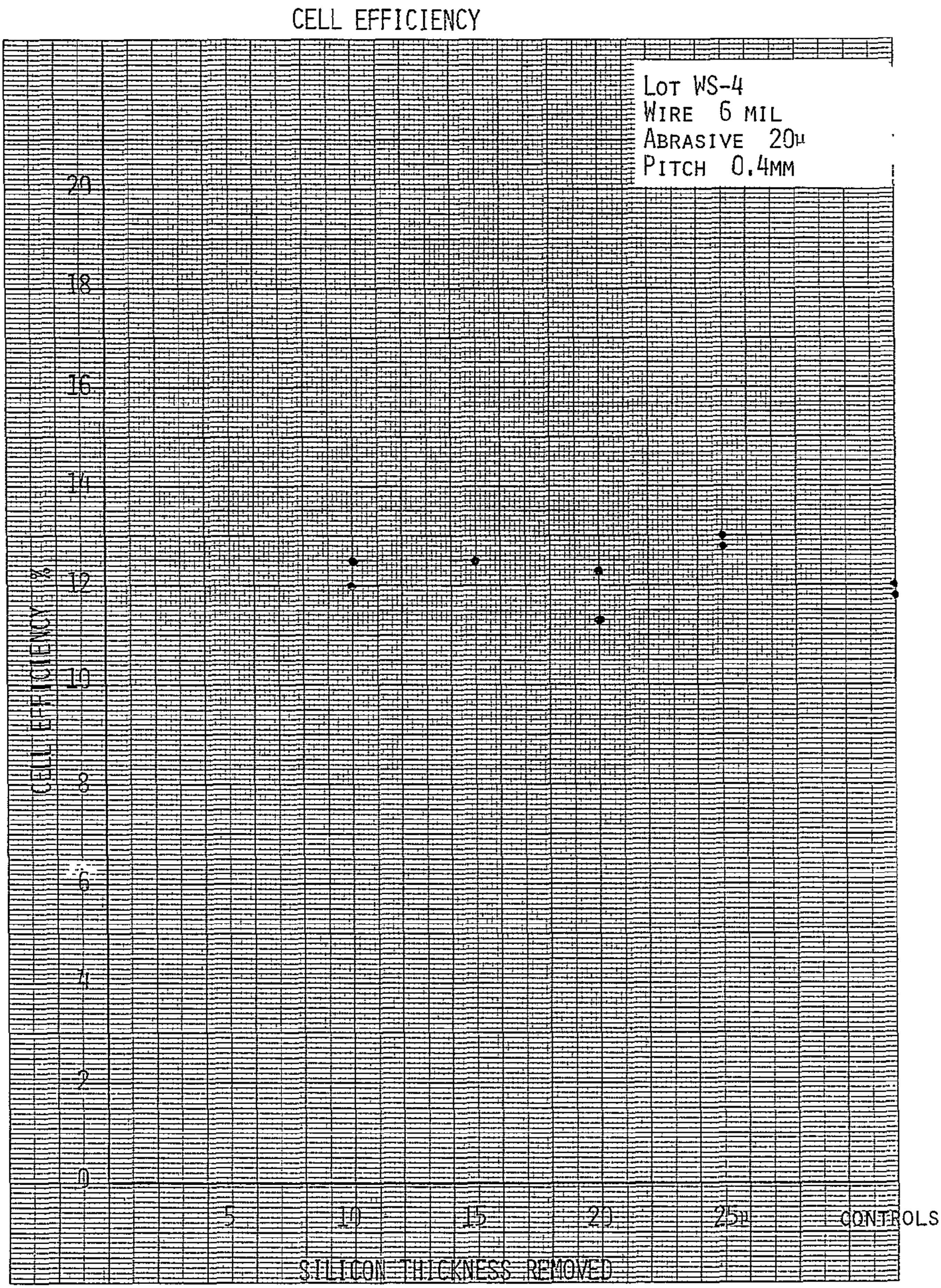

CELL EFFICIENCY
LOT WS-4
WIRE 6 MIL
ABRASIVE 20μ
PITCH 0.4MM
CELL EFFICIENCY %
20
18
16
14
12
10
8
6
4
2
0
5
10
15
20
25μ
CONTROLS
SILICON THICKNESS REMOVED

Figure 15.-1

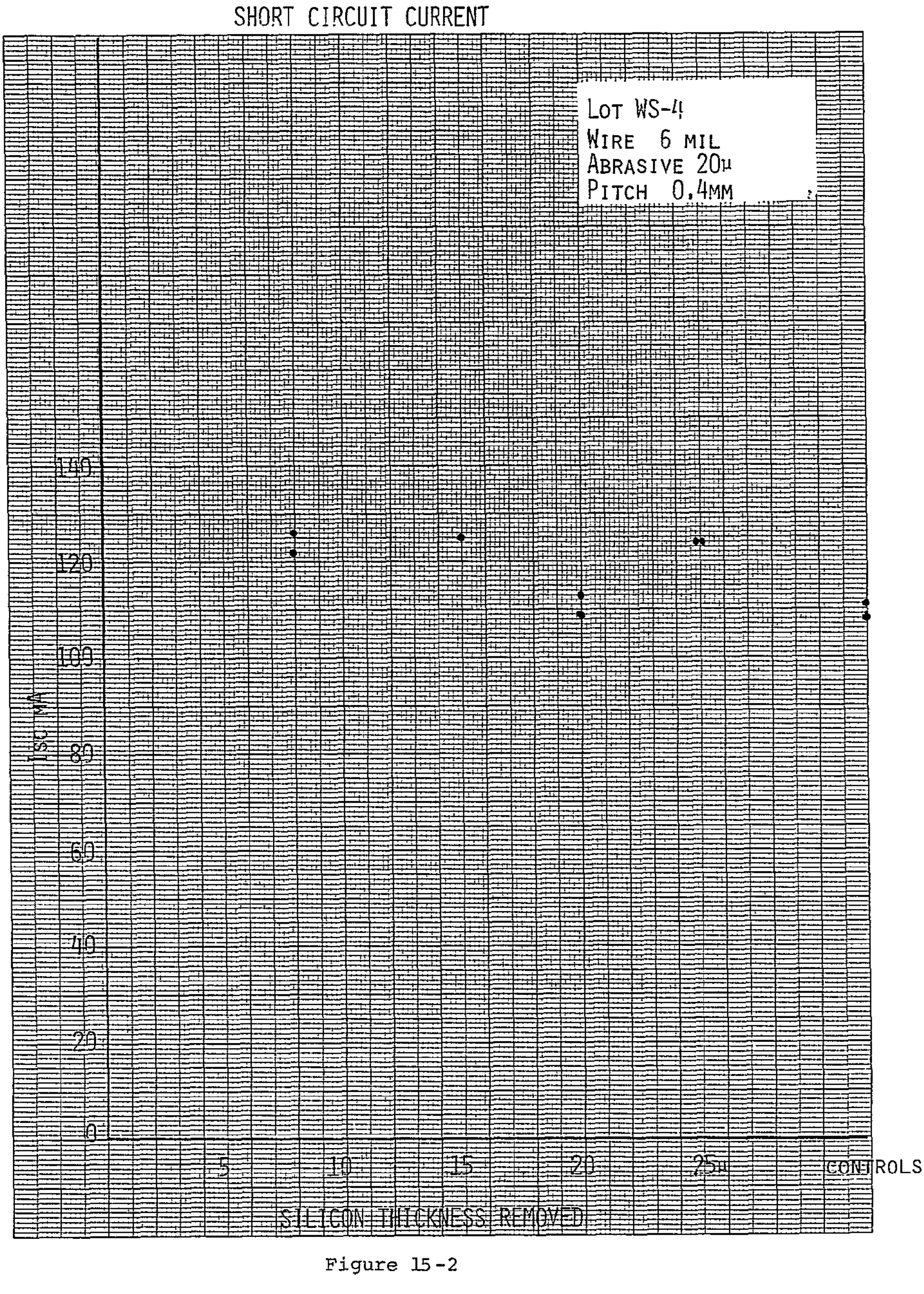

SHORT CIRCUIT CURRENT
LOT WS-4
WIRE 6 MIL
ABRASIVE 20μ
PITCH 0.4MM
140
120
100
80
60
40
20
0
ISC MA
5
10
15
20
25μ
CONTROLS
SILICON THICKNESS REMOVED

Figure 15-2

FILL FACTOR

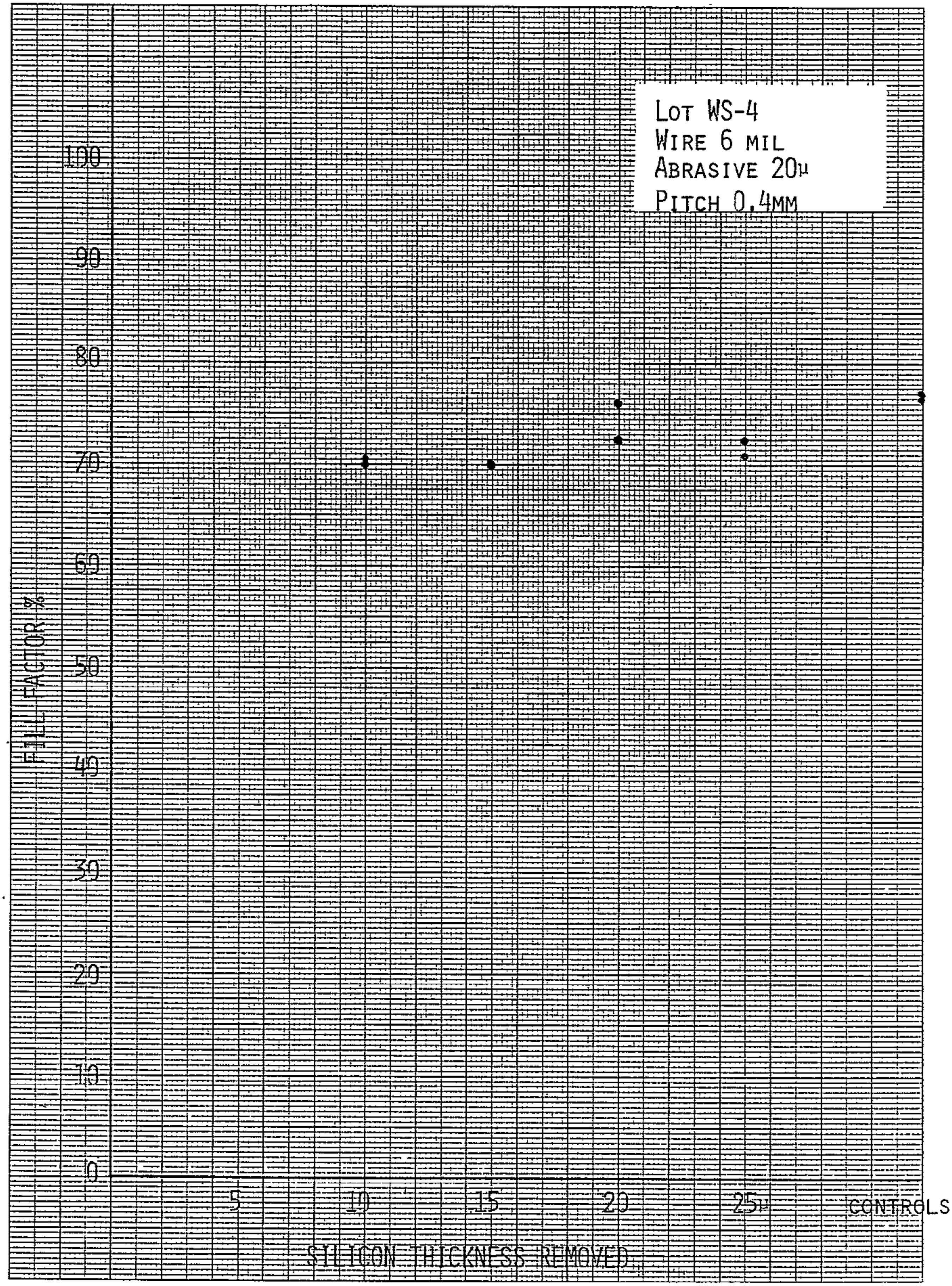


Figure 15-3

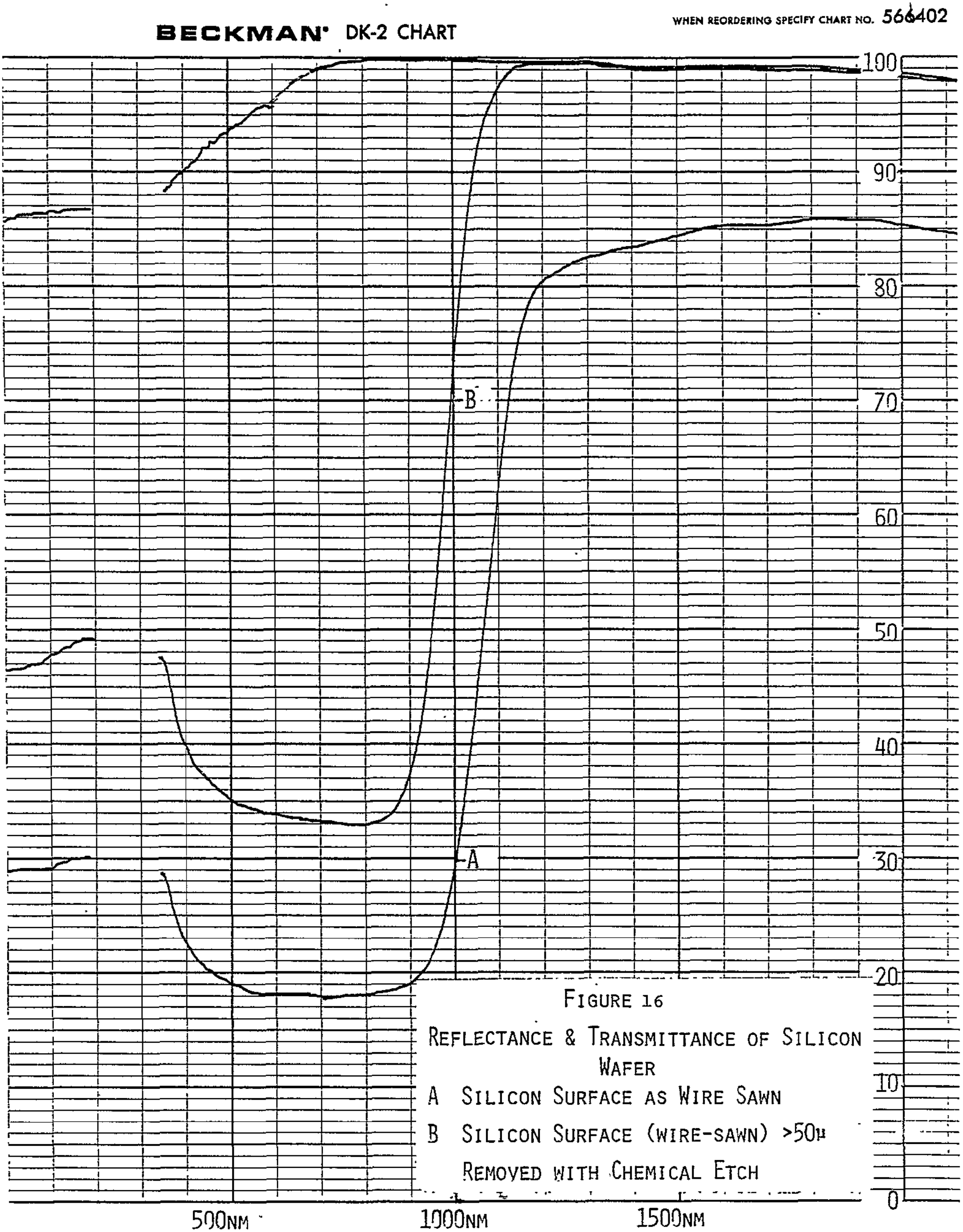


FIGURE 16

REFLECTANCE & TRANSMITTANCE OF SILICON WAFER

A SILICON SURFACE AS WIRE SAWN

B SILICON SURFACE (WIRE-SAWN) >50μ REMOVED WITH CHEMICAL ETCH

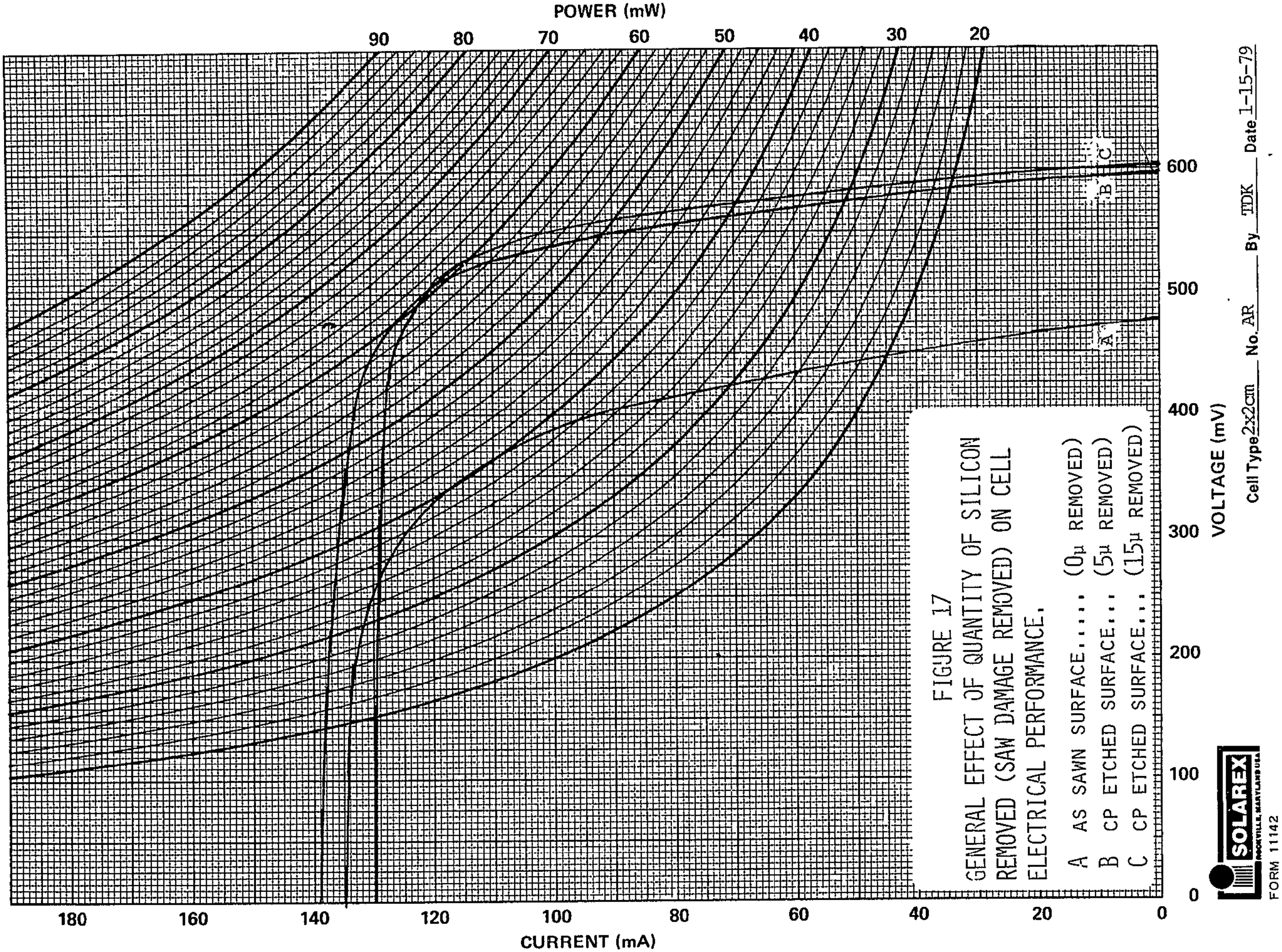


FIGURE 17
GENERAL EFFECT OF QUANTITY OF SILICON REMOVED (SAW DAMAGE REMOVED) ON CELL ELECTRICAL PERFORMANCE.

A AS SAWN SURFACE..... (0μ REMOVED)
B CP ETCHED SURFACE... (5μ REMOVED)
C CP ETCHED SURFACE... (15μ REMOVED)

Conclusions and Recommedations

The Yasunaga saw operates reliabily within the range of parameters mentioned below. Solarex developed wire winders, steel spools and improved slurry have helped to produce this level of reliability. The product wafers are flat to specfication (± 12 microns). The yield of wafers from each cut made within the operable parameters is good ($\bar{x}$ 96.87% s 4.3%).

Results of variations in saw operating parameters - wire diameter, pitch, and abrasive indicate that the minimum reliable wire diameter is 6 mil. The minimum pitch used with full success is .4mm; area yield $10.8 cm^2 g^{-1}$. However, further investigation of a .3mm pitch is warranted since its effective use may increase the number of silicon wafers produced from each 100mm ingot length saw run by 33%.

Thus far, any electrical effect of abrasive size variations has not been seen. Cutting time is, however, inversely proportional to abrasive size.

The first few cell processing runs indicate that very little silicon etching is necessary to remove sawing damage (10-20μ).

Completion of cell processing and evaluation for all the wafering saw runs will more fully explain the effects of saw operating variables on electrical performance.

Updated Program Plan

The Contract Program Plan/Schedule is depicted in Table IV. There are no Jet Propulsion Laboratory action items at this time.

ONE YEAR

PROPOSED PROGRAM PLAN/SCHEDULE (page 1 of 2)
Contract No. 955077

TABLE IV
EVALUATION OF THE TECHNICAL FEASIBILITY AND EFFECTIVE COST OF VARIOUS WAFER THICKNESSES FOR THE MANUFACTURE OF SOLAR CELLS

	TECHNICAL TASKS	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN			
1	I PROCESSING												
2	A Sawing Thin Wafers						△						
3	B Fabricate Ultrathin Cells						△						
4	C Fabricate Modules						△						
5	II CHARACTERIZATION												
6	A Characterize wafers as a function of sawing parameters						△						
7	B Characterize cells as a function of wafer thickness						△						
8	C Characterize Modules						△						
9	III ANALYSIS												
10	A Economic Evaluation of various thickness of wafers						△						
11	B Determine panel array, stiffness												
12	Requirements and Associated												
13	Weight & Cost					△							
14	C Evaluate Cells and Modules com-												
15	pared to Conventional 8 12 mil												
16	cells and modules						△						
17	IV REPORTING												
18	Monthly technical and financial reports	▲	▲	▲	▲	▲	▲						
19	Quarterly Reports				▲								
20	Program Plan/Schedule Baseline												
21	Cost Estimated					▲							
22	Draft Final Report							△					
23	Delivery of Final Report									△			

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ONE YEAR

Contract No. 955077

EVALUATION OF THE TECHNICAL FEASIBILITY AND EFFECTIVE COST OF VARIOUS WAFER THICKNESSES FOR THE MANUFACTURE OF SOLAR CELLS

		OCT	NOV	DEC	JAN	FEB	MAR						
1	1st Thin wafers sliced												
2	Specify wafer characterization sequence												
3													
4	Specify Final Wafering Variables												
5													
6	TECHNICAL TASKS												
7	Specify Cell Processing	▲											
8	1st Thin Cells Processed		▲										
9	Begin Cell Testing			▲									
10	Begin Module Fabrication				▲								
11	Complete Panel Analysis					▲							
12	Complete two Modules						▲						
13	Deliver Sample Cells & Modules						▲						
14	Complete Economic Analyses						▲						
15													
16													
17													
18													
19													
20													
21													
22													
23													

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Planned Activities

The Wire Saw is operating well at this point; wire winders, steel spools and improved slurry have solved early problems. In the next quarter, attention will be directed to the wire/workpiece constant loading mechanism, This and other variations in operation may impact on the problem of non-uniform cutting rate for certain wires. The .3mm chaser bit is being rebuilt and will be used to check the feasibility of area yields/gram of $14.3 cm^2 g^{-1}$.

Wafering demonstration runs to complete the proposed matrix (Table I) will continue. These wafering runs are almost complete; and some variations will be made in the run parameters in light of results of cell electrical evaluation.

Cell processing and evaluation will be carried out for all of the Wafering Demonstration Runs reported in this quarter. Cell performance of wafers with variously damaged silicon surfaces will be processed with various amounts of damaged silicon etched away. Cell performance as a function of final cell thickness will be characterized. Panel and array engineering requirements will be developed. Cells will be processed for two 9200 panels; the panels will be built, evaluated and delivered.